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Pilot error versus sociotechnical systems failure? A distributed situation awareness analysis of Air France 447

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Abstract

The Air France 447 crash occurred in 2009 when an Airbus A330 stalled and fell into the Atlantic Ocean, killing all on board. Following a major investigation the French accident investigation authority concluded that the incident resulted from a series of events that began when the autopilot disconnected after the aircraft's Pitot tubes froze in an adverse weather system. The findings place scrutiny on the aircrew's response to this, pointing to their lack of awareness of what was going on and of what procedure was required, and their subsequent failure to control the aircraft. This reflects a tendency for accident investigations to cite poor or loss of situation awareness on behalf of pilots as a key causal factor in aviation incidents. This article argues that this is inappropriate, instead offering a systems level view that can be used to demonstrate how systems, not individuals, lose situation awareness. This is demonstrated via a distributed situation awareness description of the events preceding the crash. The findings demonstrate that it was the sociotechnical system comprising aircrew, cockpit and aeroplane systems that lost situation awareness, rather than the aircrew alone. In closing, the importance of taking a systems view when examining concepts such as situation awareness during accident events is articulated.

Keywords: Air France 447, Distributed Situation Awareness, Aviation, Accident Analysis

Introduction

On the 31st May 2009 Air France flight AF447 stalled and crashed into the Atlantic Ocean, killing all 228 people on board. Following a major investigation, the Bureau d'Enquetes et d'Analyses (BEA), the French authority responsible for civil aviation accident investigations, concluded that the accident resulted from a succession of events that began when the aircraft's Pitot tubes froze upon entry into an adverse weather system and ended when the aircraft stalled and fell, at around 11,000ft per minute, into the ocean. Inevitably, the investigation report places significant emphasis on the aircrew's inability to understand and respond to the situation that arose following the freezing of the Pitot tubes, whereby the autopilot disconnected and the plane required manual control. Following some confusion the pilots' were seemingly unaware that the plane had entered a stall and was descending rapidly towards the ocean. Specifically, the BEA reported that the crew failed to make a link between the loss of indicated airspeeds and the appropriate procedure, made a late identification of the deviation from flight path, and failed to identify the approach to stall and subsequent stall situation itself (BEA, 2012). The following extract translated from the black box voice recorder clearly demonstrates the level of confusion on the flight deck (Popular Mechanics, 2011):

02:11:21 *Pilot Not Flying (PNF)*: We still have the engines! What the hell is happening? I don't understand what's happening.

02:11:32 *Pilot Flying (PF)*: Damn it, I don't have control of the plane, I don't have control of the plane at all!

02:11:37 *PF*: Left seat taking control!

02:11:43 *Captain (returning from rest)*: What the hell are you doing?

02:11:45 *PF*: We've lost control of the plane!

02:11:47 *PNF*: We've totally lost control of the plane. We don't understand at all... We've tried everything.

The conclusions regarding the aircrew’s role in the incident relate directly to the concept of situation awareness (Endsley, 1995); specifically the aircrew’s understanding of the unfolding situation following the autopilot’s disconnection. The findings presented in the investigation report allege that the aircrew were not aware of various aspects of flight and of what procedure was required, and so could not respond to the unfolding situation in an appropriate manner. This is not a unique position to take in accident investigation reports, and reflects a trend in which human operators are implicated for their role in accidents due to having ‘lost situation awareness’ or because they had ‘poor situation awareness’ (Dekker, 2015). This focus on human operators and their own awareness remains despite systems thinking (e.g. Leveson, 2004; Rasmussen, 1997) now being widely accepted as the most appropriate approach to accident investigation (Underwood and Waterson, 2014). This viewpoint clearly articulates that accidents are caused by the interaction of the decisions and actions of multiple human and technical elements, rather than one failure in isolation.

Recently researchers have questioned this fixation on loss of situation awareness, citing moral, ethical, and theoretical issues associated with labelling an individual's loss of situation awareness as the cause of incidents (e.g. Dekker, 2015; Salmon et al, 2015). This article builds on these arguments by demonstrating that this inappropriate and perhaps misunderstood use of situation awareness threatens its potential contribution to safety science (Salmon and Stanton, 2013). Particularly problematic is the fact that focussing on individual cognition during accident investigation inevitably leads to countermeasures which focus on fixing human operators through avenues such as retraining and reprisals, an approach that has long been known to be inappropriate (Dekker, 2002; Reason, 1997). What makes this state of affairs more worrying is that, in ignoring advances in the human factors knowledge base and returning to individual operator-focussed concepts, our discipline may no longer be doing what it should be – supporting the design of safe sociotechnical systems in which humans are viewed as assets rather than the source of problems.

In order to remain useful in accident investigation and accident prevention efforts, it is these authors' opinion that a shift in the way in which situation awareness is considered in the aftermath of adverse events is required. Specifically, it is argued that situation awareness can only be meaningful in this context when considered from a systems perspective; that is, when situation awareness plays a role in incidents, it is the system itself that loses situation awareness, not the individuals working within it (Salmon et al, 2015). Why the system lost situation awareness should then be the explicit focus of accident investigations, not which individuals lost situation awareness and what cognitive flaws made this possible. This argument is articulated through first briefly outlining a systems level model of situation awareness, known as Distributed Situation Awareness (DSA; Salmon et al, 2009: Stanton et al, 2006), and second through presentation of a DSA-based analysis of the Air France incident. Together the model and the analysis demonstrate the utility of systems thinking in the context of situation awareness and its role in adverse events.

Situation awareness: something that is held by people or by systems?

Distributed Situation Awareness (DSA)

Although much early research on situation awareness focussed on the awareness held by individual human operators (e.g. pilots, drivers, soldiers), as evidenced by this special issue, there has been a significant shift over the last decade towards models that view situation awareness as a systems level phenomena (e.g. Stanton et al, 2006; Salmon et al, 2009). Based on a program of research focussing on command and control systems in defence and civilian domains, Stanton et al (2006) and Salmon et al (2009) proposed a model of DSA that attempted to shift the unit of analysis from individuals and teams to sociotechnical systems. Inspired by Hutchins seminal work on distributed cognition, the DSA model argues that situation awareness is an emergent property that is held by the overall system and is built through interactions between 'agents', both human (e.g. human operators) and non-human (e.g. tools, documents, displays). Further, the model purports that situation awareness is not held by any one agent alone but instead resides in the interactions occurring across the sociotechnical system.

There are various in-depth descriptions of the DSA model presented in the literature (see Salmon et al, 2009; Stanton et al, 2009) and no doubt in this special issue. There are, however, some important facets worth discussing here. In the original paper specifying the DSA model, Stanton et al. (2006) indicate how the system can be viewed as a whole, by consideration of the information held by the human and non-human agents and the way in which they interact. The dynamic nature of situation awareness means that it changes moment by moment, in light of changes in the task, environment and interactions (both social and technological). DSA is considered to be activated knowledge for a specific task within a system at a specific time by specific agents. Whilst this can be conceptually challenging from a cognitive psychology perspective, from a systems perspective it is not (e.g. Hutchins, 1995; Rasmussen, 1997; Leveson, 2004; Wilson, 2012).

Stanton et al (2015) clarify this by describing how systems have a network of information elements, linked by salience, being activated by tasks and belonging to different agents – something akin to a hive mind of the system (Seeley et al, 2012). Within this network nodes are activated and deactivated as time passes in response to changes in the task, environment and interactions. Viewing the system as a whole, it does not matter if humans or technology own this information, just that the right information is activated and passed to the right agent at the right time. Further, it does not matter if the human agents do not know everything, provided that the system has the information and enables it to perform effectively (Hutchins, 1995).

Agents are able to compensate for each other, enabling the system to maintain safe operation.

A key facet of the DSA model is the notion of ‘transactions’ between agents as the mechanism that enables a system to maintain DSA throughout the course of a task. A transaction in this case represents an exchange of situation awareness between agents and so refers to more than the mere communication of information to incorporate the resulting impacts on DSA (see Neville et al, this issue). Agents interact with one another, receive information, it is integrated with other information and acted on, and then passed onto other agents (Stanton et al, 2009). The interpretation of that information changes per agent. For example, information regarding airspeed may rightly be used and interpreted differently by the Pilot Flying (PF) and the Pilot Not Flying (PNF), as it is integrated with other information to enable each to perform their own tasks. The exchange of information between agents also leads to transactions in the situation awareness being passed around; for example, a pilot’s request for information gives clues to the other pilot what the other agent is working on. Both are using the information for their own ends, integrated into their own schemata, and reaching an individual interpretation. Aspects of situation awareness from one agent can form an interacting part of another’s without any necessary requirement for parity of meaning or purpose. Notably, it is these transactions that hold the key to safe and efficient performance within aviation and indeed other complex sociotechnical systems; without them, the system cannot maintain the appropriate level of situation awareness required to achieve its goals. Post accidents, this means that investigators need to understand not only what awareness was lost, but what transactions involving human and non-human agents were either inadequate or were required but not forthcoming.

DSA and accident investigation

This systems level view demands a different approach to accident investigation. Importantly, it means that judging a pilot to have poor situation awareness alone becomes almost meaningless, because this is not placed in the context of the systems DSA. Indeed, the arguments presented in this paper centre around the notion that loss of situation awareness by any individual cannot possibly be labelled as the cause of an accident. Not because loss of situation awareness doesn't happen, rather, because focussing on individuals losing situation awareness is neither appropriate nor useful. This is because, systems hold situation awareness and therefore lose situation awareness, not the individuals working within them.

When loss of situation awareness seems to have played a role in an adverse event, accident investigators need to examine why the system's DSA was degraded, not who lost awareness. For example, investigations should ask questions such as why were the aircrew were not aware of something important? Why did the requisite transactions not occur? Why did the system not have enough DSA? When 'loss of situation awareness' takes place, is it not appropriate to begin with the individual and try to expand outwards. Rather, in line with DSA, a systems approach is required, whereby one starts with the system and focuses inwards. Especially important are the transactions in awareness that occurred in the lead up to the incident.

Situation awareness networks

Rather than try and understand the 'component' humans in the system by analysing their individual cognition, DSA bypasses this by focussing on the interactions and transactions between them. By focussing on transactions, it is possible to generate situation awareness networks comprising concepts and the relationships between them (see Figure 1 which shows an extract of such a network). This effectively provides a picture of the systems awareness at different points in time. Through further interrogation it is possible to determine who in the system had access to what knowledge at different points in time (e.g. Stanton et al, 2006). Moreover, it is possible to trace the impact of the transactions (or lack of transactions) over time; in turn this makes it possible to model the degradation of a system's awareness in the lead up to the adverse event. This approach has been successfully applied in various domains for various purposes, including accident investigation (e.g. Griffin et al, 2008; Rafferty et al, 2012; Salmon et al, 2011).

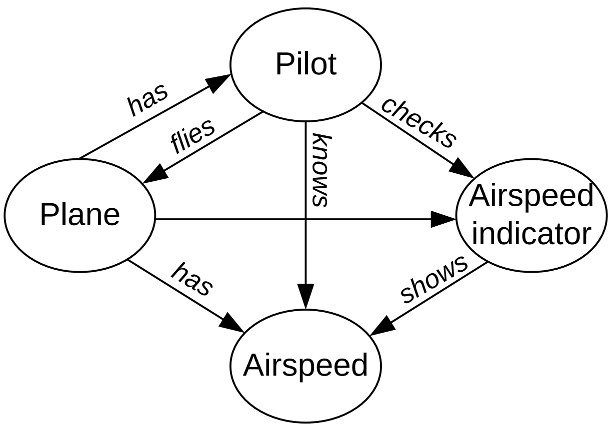

Figure 1. Example situation awareness network showing relationships between concepts.

For example, based on a DSA-based analysis of the Kegworth Boeing 737-400 crash, Griffin et al (2008) found that various transactional failures played a key role in the crash. Further, Griffin et al (2008) concluded that failures in transactions lie at the root of all adverse aviation events and that, when examining them, one should not distinguish between human and non-human agents.

Air France 447 case study

The tragic events of Air France 447 provide an appropriate case study to further examine the extent to which the DSA perspective can be usefully applied to the analysis of accidents in complex sociotechnical systems. Accordingly, situation awareness networks were used to examine the events leading up to the Air France flight AF 447 incident. The aims of the study were to test the notion that, in modern day accidents, loss of situation awareness can be meaningfully considered at a systems level, as opposed to an individual operator level, and to further examine the utility of the situation awareness network method as an accident investigation approach.

The Air France crash and timeline of events

In order to understand the Air France incident and the context in which it occurred it is first necessary to describe the timeline of events leading up to and including the incident. The overview presented below is based on the information presented in the BEA investigation report (BEA, 2012).

The incident occurred on the 31st May 2009 during a scheduled passenger flight from Rio de Janerio, Brazil, to Paris, France. Just over three and a half hours after departure, at approximately 2.02am Coordinated Universal Time (UTC), the Captain left the flight deck to take a scheduled rest break. Shortly afterwards, at 2.03.44am, the PF noted that the plane had entered the Intertropical Convergence Zone (ITCZ), which is an area close to the equator that experiences consistently severe weather. The PF subsequently called through to a flight attendant to warn of impending turbulence and the need to take care. The aircraft's anti-icing system was then turned on.

Upon entry into the ITCZ the aircrafts pitot tubes froze due to the low air temperature. Shortly before 2.10am an alert sounded in the cockpit to notify the pilots that the autopilot was disconnecting. At 2.10.06am, the PF remarked, "I have the controls" and was acknowledged by the PNF. Following this, the PF put the aeroplane into a steep climb by pulling back on his sidestick, triggering a stall warning which subsequently sounded 75 times for the remainder of the flight. The plane gained altitude rapidly but lost speed quickly. The PF continued to apply nose up inputs with the PNF apparently unaware of this. Eventually the aeroplane went into a stall and began to lose altitude. After trying unsuccessfully to identify the problem and an appropriate procedure, the PNF called the Captain back into the cockpit. At 2.11.32am, the PF announced "I don't have control of the plane". At 2.11.37am the PNF took control of the aeroplane. Six seconds later the Captain returned to the cockpit and subsequently attempted to diagnose the situation. Both the PF and PNF informed the Captain that they had lost control of the aircraft and did not understand why. At 2.13.40am the PF told the Captain that he had ‘had the stick back the whole time’, at which point the PNF took control of the plane and applied nose down inputs in an attempt to prevent the stall and gain speed. Unfortunately these actions were taken too late, and at 2.14.29am the voice recorder stopped as the plane crashed into the ocean.

DSA analyses typically involve describing a systems awareness across distinct task phases (Stanton et al, 2013). For the purposes of the present DSA analysis the incident was decomposed into the following key phases:

1. *Phase 1*. Entrance into the ITCZ until autopilot system disconnection.
2. *Phase 2*. Aircrew’s initial response to autopilot disconnection
3. *Phase 3*. Return of Captain to cockpit

The analysis involved constructing situation awareness networks for each of the three phases.

Methodology

Initially, one human factors analyst with significant experience in applying the DSA model, the situation awareness network method, and the application of accident analysis methods in various domains constructed situation awareness networks for each of the three phases. This component of the analysis used the ‘Analysis’ section of the BEA investigation report (section 2 of the report, pgs. 167 – 182 which details the unfolding events following entry into the intertropical convergence zone) along with a translation of the corresponding cockpit voice recordings as the primary data inputs.

The network construction process involved reviewing the information in the report and transcript to identify situation awareness concepts (e.g. nodes in the networks e.g. pitot tubes, ice) and the relationships between them (e.g. Pitot tubes □ Ice). For example, from the sentence “From 2 h 01, the PF mentioned the subject of the ITCZ, turbulence and the choice of flight level in his briefing to the co-pilot who joined him as relief for the Captain” (BEA, 2012, p169), the concepts *ITCZ* (Intertropical Convergence Zone), *turbulence*, *flight level* and *briefing* were extracted. In addition, relationships between ‘briefing’ and ‘ITCZ’, ‘turbulence’ and ‘flight level’ were recorded. This process enabled an overall situation awareness network to be built for each of the three event phases.

An additional aspect of the analysis involved identifying aspects of situation awareness that the report described the pilots or cockpit systems as not having (and thus representing the ‘lost’ parts of situation awareness). Missing concepts were identified by extracting concepts that the report suggested that the aircrew or cockpit systems should have known. For example, from the sentence “the PNF did not consider the warning to be relevant in the context of the fact that he was not necessarily aware of: The PF’s significant nose-up inputs that generated an increased angle of attack; The relative proximity of a flight envelope limit; The reconfiguration to alternate law” (BEA, 2012, p173-174), the missing concepts ‘PFs control inputs’, ‘Proximity to flight envelope limit’ and ‘Mode change (reconfiguration to alternate law' were identified. This process produced a list of missing situation awareness concepts associated with each situation awareness network. These represent the pieces of information that the pilots could have used to help understand the situation, respond appropriately, and prevent the adverse outcome that occurred.

Upon completion of the initial analyses, the first analyst (analyst 1) was joined by an additional human factors analyst with extensive experience in applying DSA and accident analysis methods (analyst 2). The two analysts then recoded the BEA investigation report and refined the original networks, with any discrepancies or disagreements' being resolved through discussion until consensus was reached. Finally, a third analyst (analyst 3), also with extensive experience in applying DSA and accident analysis methods reviewed the BEA investigation report and constructed situation awareness networks for each phase independently, identifying relevant and missing situation awareness concepts and the relationships between them. A subsequent comparison of third analyst's coding with the coding from analysts 1 and 2 revealed a percentage agreement of 91% for the concepts within the situation awareness network, and 75% agreement between them for the missing concepts. The three analysts then subsequently met and resolved any differences to produce the final networks presented in Figures 2, 3 and 4. A comparison of the agreement between the relationships between concepts identified by the analysts was not undertaken as it was out of the scope of the present study; however, little disagreement was encountered when finalising the networks.

Results

The situation awareness networks for phases 1, 2 and 3 are presented in Figures 2, 3 and 4. Where appropriate important contextual pieces of information are shaded within the networks. For example, in the phase 1 network below the airspeed concept is shaded (as this information triggered the autopilot disconnection) along with the warnings that signalled the autopilot disconnection and the disconnection itself. In addition, the missing concepts for each phase are listed on the right hand side of each Figure.

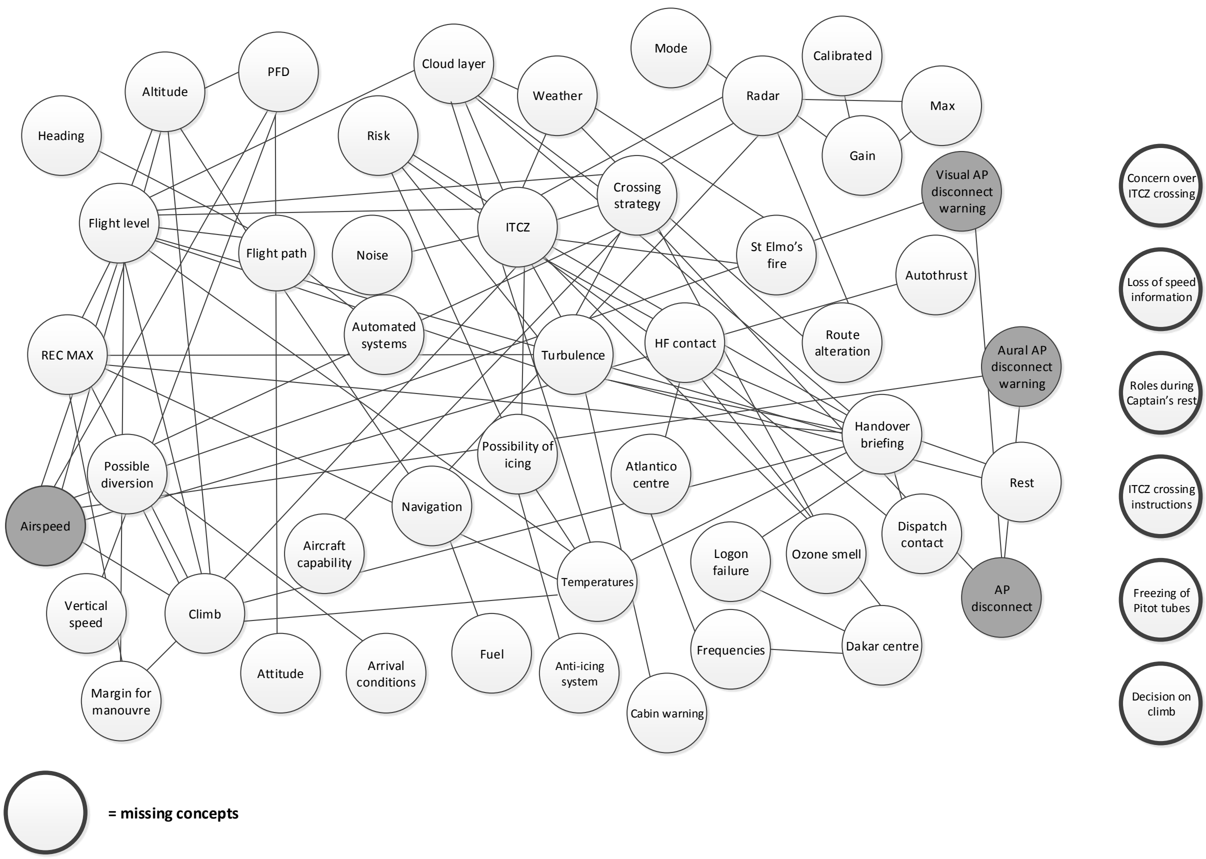

Figure 2. Phase 1 situation awareness network

Figure 2 shows the situation awareness network covering the information being used between the entrance into the ITCZ and the autopilot's disconnection. An important concept within this network is the airspeed concept – spurious airspeeds were sent to the cockpit because the pitot tubes were frozen. This transaction in awareness led to the autopilot disconnection and triggered the unfolding events. It is notable that this was a transaction between technological agents rather than human agents. The majority of the other concepts within the phase 1 network relate to standard flight parameters and systems.

A number of missing concepts are also represented. The first relates to the PFs concern over the crossing into the Inter-tropical convergence zone. The PF had expressed a number of concerns over the crossing and suggested changing flight level to fly above the clouds; however, according to the report the Captain was unresponsive, instead favouring waiting and responding to any issues as they arose. The second concept is the loss of speed information – here the crew were alerted to the disconnection, but not the issue with the airspeeds. The third missing concept relates to the roles adopted by the PF and PNF during the Captains rest period. As the incident played out an assertion of authority is made by the PNF; however, no discussion was held over roles during the rest period. Similarly, the fourth missing concept relates to the instructions or strategy for crossing the inter-tropical convergence zone. According to the investigation report the Captain didn't make any judgements on the situation that they faced crossing into the zone, and he didn't leave any tactics or instructions for the crossing itself. The fifth missing concept here is the actual freezing of the pitot tubes – the report does not provide any information to suggest that the pilots were aware of this. It appears that no transaction took place to alert the aircrew of this (although they would have been aware that freezing pitot tubes was an issue). The sixth and final missing concept ‘decision on climb’ relates to the fact that the Captain did not respond with a decision or strategy to the PFs request to climb above the cloud cover to avoid turbulence.

Once the speed anomalies were detected, the autopilot disconnected, and this was signalled by both a visual and aural warning within the cockpit (see shaded concepts in Figure 2). Figure 3 shows the situation awareness network following the disconnection up until the Captain returned the cockpit. It is important to note that the period of time covered by the network in Figure 3 is approximately one minute and 37 seconds.

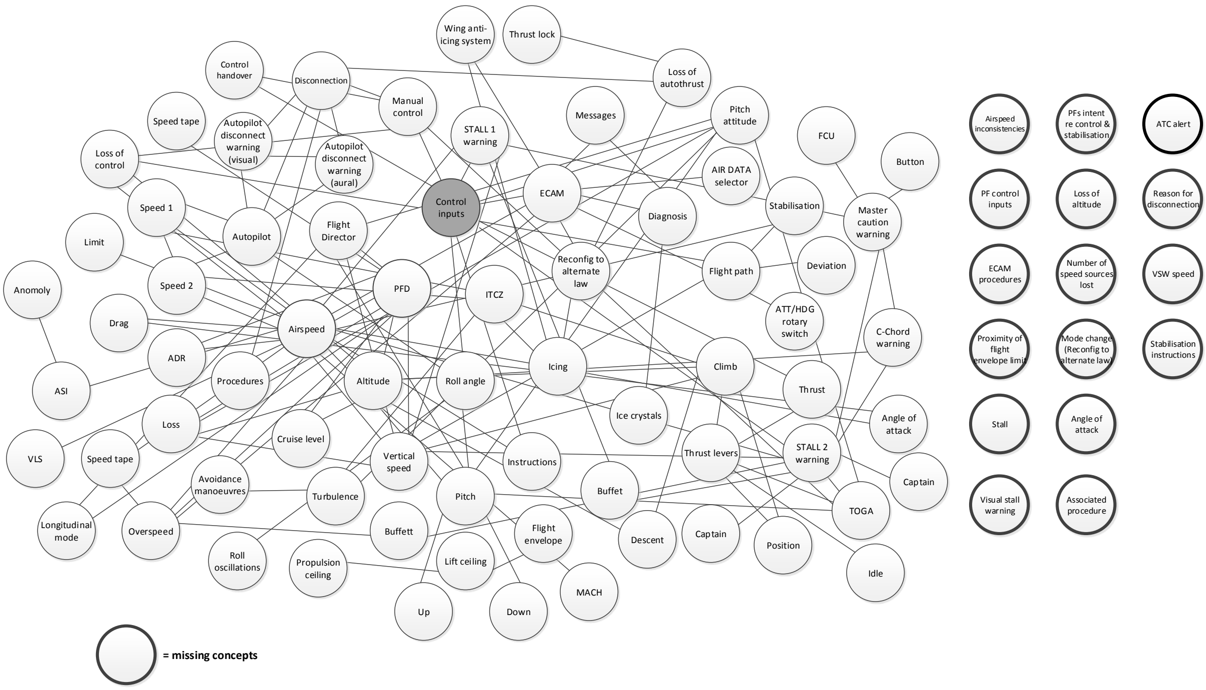

Figure 3. Phase 2 situation awareness network

The first thing to note is that the network for phase 2 is bigger and more complex – indicating a complex scenario in which information overload seemingly played a role. An important concept within the network for phase 2 is the PF’s control inputs (shaded). These were inappropriate, putting the aeroplane into a nose up climbing position. The investigation report identifies many pieces of information that the either the PF, PNF, or both, were not aware of during this phase. The first interesting group of missing concepts relate to the PFs control inputs. According to the report the PNF wasn’t aware of what control inputs the PF was making, and he wasn’t aware of what the PFs intentions around control inputs were as they were not communicated. An important note to make here is that, in the A330 the PFs sidestick control inputs cannot be observed easily by the other pilot so control input information represents both a human to human transaction and a non-human to human transaction in awareness.

The second interesting group of concepts relate to the Electronic Centralized Aircraft Monitor display (ECAM). The ECAM monitors the aircrafts functions and systems and provides information the aircrew regarding failures and appropriate response procedures. According to the investigation report, initially the ECAM did not display any information pointing to a speed indication problem and also displayed a range of confusing messages. The report also highlights the fact that no relevant procedure was displayed via the ECAM (one of its primary functions). Another interesting concept that apparently wasn’t understood for a time was the reconfiguration to alternate law – it is suggested in the report that the pilots were not aware that the plane had reconfigured to alternate law. A result of this is that they may have believed that the plane could not stall as it was being protected via the normal law flight mode. The stall warnings and indeed stall itself also feature in the missing concepts. According to the investigation report the crew did not refer to or discuss the stall warnings, which brings into question whether they were ever aware that the plane was in a stall situation. It is unclear why this was the case – the report cites the high workload associated with diagnosing the situation, and also the possibility that the pilots thought they were actually in an overspeed situation. This relates to the lack of awareness regarding the mode shift - if the PF did not understand that they were flying in alternate law he could have thought that it was impossible to stall the plane. A final interesting missing concept relates to the fact that Air Traffic Control couldn't monitor the flight as there was a failure to connect with DAKAR Oceanic ACC. If this connection had been made then the loss of altitude would have generated an alert on the relevant air traffic controller's screen.

Figure 4 shows the situation awareness network from when the Captain returned to the cockpit to the point at which the plane impacted the ocean.

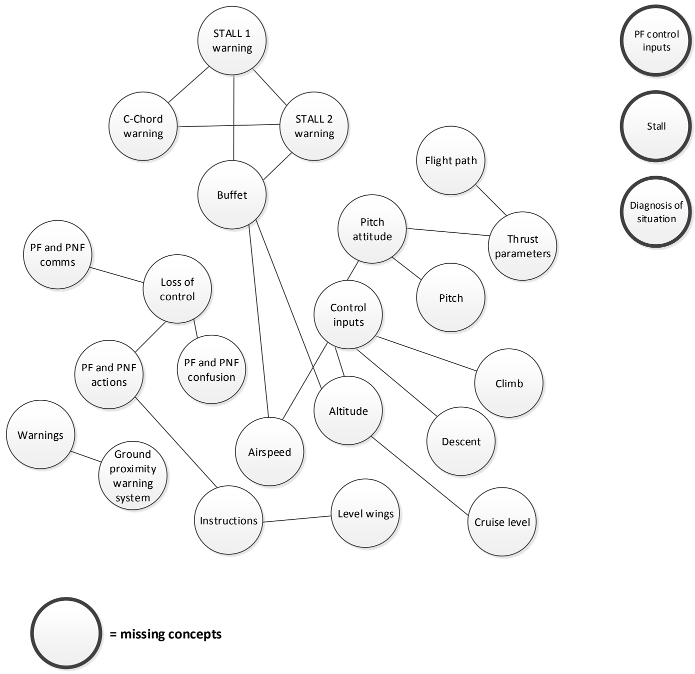

Figure 4. Phase 3 situation awareness network

The network presented in Figure 4 shows that the system at this point had degenerated to a series of warnings and attempts to diagnose the situation. Indeed, the missing concepts during this phase of the incident include the stall, the PF's inputs, and a diagnosis of the situation. Eventually these concepts became part of the network when the PF told the Captain that he had 'had the stick back the whole time'. At this point the PNF took control of the plane and applied nose down inputs in an attempt to prevent the stall and gain speed. Unfortunately these actions were taken too late, and at 2.14.29am the plane crashed into the ocean.

Based on the networks presented it is possible to identify a number of different ways in which the situation awareness transactions failed. Examples of the different forms of transaction implicated in the incident, along with the agents involved, is presented in Table 1.

Table 1. Examples of the transactions in awareness that either played a role in the incident or could potentially have prevented the incident

Phase 1: Entry into tropical convergence zone to disconnection of autopilot		
Transaction Failure type	**Transaction required**	**Agents involved**
Absent transaction	When he left the cockpit for his rest break the Captain had not discovered the PF's level of concern over crossing into ITCZ	Captain and PF
Absent transaction	The risk of loss of speed information related to high density ice crystals was not discussed between the PF and the PNF	PF and PNF
Absent transaction	Definition of co-pilot roles during Captain flight rest time	Captain, PF and PNF
Absent transaction	Before leaving the cockpit for his rest break the captain did not leave any instructions regarding the ITCZ crossing	Captain, PF and PNF
Absent transaction	No explicit indication in the cockpit informing the aircrew that the pitot tubes had frozen	Pitot tubes, cockpit displays, PF and PNF

Inappropriate transaction	Inappropriate airspeed information	Pitot tubes and cockpit systems
Phase 2: Aircrew's initial response to autopilot disconnection		
Transaction Failure type	**Transaction required**	**Agents involved**
Absent transaction	Reason for autopilot disconnect	ECAM, PF and PNF
Inappropriate transactions	ECAM displays succession of messages	ECAM, PF and PNF
Absent transaction	Appropriate action or procedure on ECAM	ECAM, PF and PNF
Absent transaction	PF's intentions/objectives regarding control and stabilisation of flight path	PF and PNF
Misunderstood transaction	Stall warning (STALL 1 and STALL 2)	Stall warning, PF and PNF
Absent transaction	PF's control inputs	PF, PNF, Sidesticks
Phase 3: Return of Captain to cockpit		
Transaction Failure type	**Transaction required**	**Agents involved**
Absent transaction	Discussion of stall warning	PF, PNF and Captain
Incomplete transaction	Discuss sequence of events	PF, PNF and Captain
Misunderstood transaction	Stall warning	Stall warning, PF and PNF

Based on the analysis presented it seems that four forms of transaction failure played a role in the incident. These include absent transactions, inappropriate transactions, incomplete transactions, and misunderstood transactions. Notably the agents involved in all forms of failed transaction were both human and non-human. *Absent transactions* involve instances where a transaction in awareness was required but was not initiated. This includes scenarios where the exchange should have happened but did not due to a failure of some sort and also scenarios where a transaction would have supported the systems DSA but at the time was not part of normal operation through inclusion in operating procedures or artefacts (e.g. documents, displays). *Inappropriate transactions* involve instances where a transaction in awareness was initiated, but the content of the transaction was incorrect. This includes scenarios where the human or non-human agent (e.g. display, document) initiating the transaction provided the wrong information or where the awareness being exchanged was incorrect. *Incomplete transactions* involve instances where the appropriate transaction was initiated, but the delivery was incomplete; not all information was exchanged as required. Finally, *misunderstood transactions* involve instances where the receiver misunderstands the information or picture being transacted.

Discussion

The aim of this article was to demonstrate that, in modern day accidents, loss of situation awareness can be meaningfully considered at a systems level. In addition, it is intended that the analysis presented would provide further evidence for the utility of using situation awareness networks as an accident analysis methodology.

Who lost situation awareness?

The arguments presented in the this article centre around the notion that, in most meaningful contexts situation awareness is not something that can be held by one individual alone, and therefore cannot be lost by one individual alone (Salmon et al, 2015). The analysis presented shows that it was the sociotechnical system comprising aircrew, cockpit and aeroplane systems that lost situation awareness, rather than the aircrew alone. This is evidenced by the fact that multiple failed transactions in awareness played a part, and that these transactions were between non-human agents (e.g. cockpit systems and displays), between non-human and human agents (e.g. cockpit displays and pilots) and between human agents (e.g. PF and PNF). Interestingly, the initial transaction that led to the incident beginning was entirely between non-human agents (e.g. the pitot tubes and the cockpit systems).

Whereby the pitot tubes and eventually the cockpit systems lost awareness of the planes airspeeds. In addition, a key feature of the incident was the inability of the aeroplanes systems to clearly inform the PF and PNF of what was going on. This included why the autopilot had disconnected, what the appropriate procedure was, what actions the PF was taking in response to the situation, and the status and associated risk of key flight parameters. Finally, examining the information that was not communicated revealed that much of the information should have been provided by the cockpit's systems. Given these characteristics of the incident it is inappropriate to point to a loss of awareness on behalf of the aircrew only.

The implication of this is that countermeasures should focus on enhancing the transactions required during both routine and non-routine flight situations. For example, what information is required, how best it can be communicated in high workload situations, and who or what it should be communicated by are important considerations. The missing information surrounding the PF's inappropriate control inputs provides an appropriate case in point. Here the PNF was not aware that the PF had been applying nose up inputs throughout the unfolding incident. By considering the role of non-human agents in DSA and examining the overall cockpit system (as opposed to the PF and PNF alone) it could be ascertained that this information should be communicated between the PF and PNF both verbally as part of the aircrew's threat and error management activities and also by the cockpit systems (e.g. via sidestick feedback). This kind of approach provides an appropriate level of redundancy for flight operations.

Situation awareness networks for accident investigation

The analysis presented provides further evidence for the suitability of using network analysis methods for accident analysis purposes. Specifically, the networks constructed were able to show where key pieces of information (or concepts) were either not understood or were simply not present in the system. A further benefit of this approach is that it is able to identify instances where required information is present within the system, but is not held by the agent or agents who require it. The outputs therefore enable investigators to pin point issues in the communication of information and facilitate the consideration of why situation awareness was lost and not a focus on who lost it.

An additional contribution of the analysis presented is to build on Griffin et al (2008), Rafferty et al (2012) and Salmon et al's (2011) use of DSA in examinations of adverse events by identifying a sub-set of transaction-related failures underpinning modern day sociotechnical system accidents. Based on the present and previous DSA analyses, four forms of transaction failure were identified. These include absent transactions, inappropriate transactions, incomplete transactions, and misunderstood transactions. It is these authors opinion that these failed transactions lie at the root of the accidents occurring in complex sociotechnical systems such as aviation, air traffic control, and process control. An important line of further research is the testing and validation of the transactional failures identified.

The transactional failures described have some noteworthy features that are brought about by the distributed cognition and systems thinking perspectives underpinning the DSA model. First, they can be applied to both human and non-human agents. The onus is not on human operators exchanging the wrong information or misunderstanding the information given to them. Rather, the onus is on the system and interactions between its components and so the issues can be associated with documents, displays, equipment and the general work environment. Nothing is off limits. Second, in line with systems thinking, it is the interaction between agents that are examined, rather than the agents themselves. For example, the focus is not on the pilot not being aware of something, instead it is on what interaction between agents that led to the appropriate awareness not being distributed as it should have been.

As a case study analysis there are limitations associated with the analysis presented. First is the fact that the analysis is based on the investigation report produced by the BEA and has not been verified by anybody involved in the investigation or the incident itself. It is not possible, therefore, to be sure that the networks presented are either complete or accurate. Indeed, it is likely that they present snapshots of the systems awareness rather than comprehensive descriptions of it. Second is the fact that a comparison of the agreement between analysts regarding the relationships between concepts identified was not undertaken. As mentioned this was not possible due to project constraints. Further, little disagreement was encountered when finalising the networks. Third and finally, the 75% agreement between analysts on the missing concepts could be criticised for being relatively low. The lower agreement rating for missing concepts was potentially found as the identification of missing concepts (as opposed to identifying present concepts) was a new form of analysis not previously undertaken by the authors. In future agreement between analysts could be enhanced through detailed clarification on what exactly constitutes a missing concept.

Conclusion

Situation awareness is a key concept for safety science (Salmon et al, 2015); however, it is not possible to improve situation awareness, performance, and ultimately safety by focussing on individual operators in the aftermath of adverse events. Whilst this is now widely accepted for accidents generally, it has not translated to traditionally individual operator concepts such as situation awareness. The analyses presented has shown that a richer description of how situation awareness plays a role in adverse events is developed by assessing events through a systems lens. This viewpoint argues that it is systems, not individuals, that lose situation awareness and therefore that systems, not individuals, should be the focus when attempting to improve performance following adverse events. It is hoped that this approach is taken during the analysis of adverse events not only in aviation but also across the safety critical domains.

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